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EVALUATION OF A NEW FRACTURE TOUGHNESS MEASURING TECHNIQUE, AND ADAPTATION OF THE TECHNIQUE TO USE ULTRA-SMALL SPECIMENS

SEPTEMBER, 1979

TERRA TEK, INC.
SALT LAKE CITY, UTAH

FINAL REPORT - CONTRACT NUMBER DAAG46-78-C-0040

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Three separate investigations were undertaken to determine the applicability of the short rod fracture toughness measurement method to materials such as HF1 fragmentation steel, which is of particular interest to the Army. In the first study, short rod fracture toughness (K_{ICSR}) measurements were compared with ASTM E 399 measurements of toughness (K_{IC}) in a number of metallic materials. Very good agreement was found. In the second study, the methods of fabricating and testing ultra-small short rod speci-

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ABSTRACT

mens (6.35 mm diameter) were developed and used in measurements of HF1 material taken from actual shell casings. The agreement of the ultra-small short rod measurements with the toughness as measured by pre-cracked charpy specimens of the same material was rather poor. The third study was made to determine the sensitivity of the short rod toughness measurement to the size of the specimen used in the test. Short rods of various sizes of 4340 steel and two heat treatments of HF1 steel were tested. The specimen size independence of the 4340 steel was marginal, but it was excellent for the HF1 steel. A trend toward an increasing scatter in K_{ICSR} data with decreasing specimen size was noted. Recommendations for decreasing the data scatter and automating the test are made.

K sub IC

FOREWORD

This study has been conducted by Terra Tek, Inc., Salt Lake City, Utah, under Contract No. DAAG 46-78-C-0040 from the Army Materials and Mechanics Research Center, Watertown, MA. Mr. F. I. Baratta served as technical monitor. The advice, guidance, and participation of Mr. Baratta in this study is much appreciated.

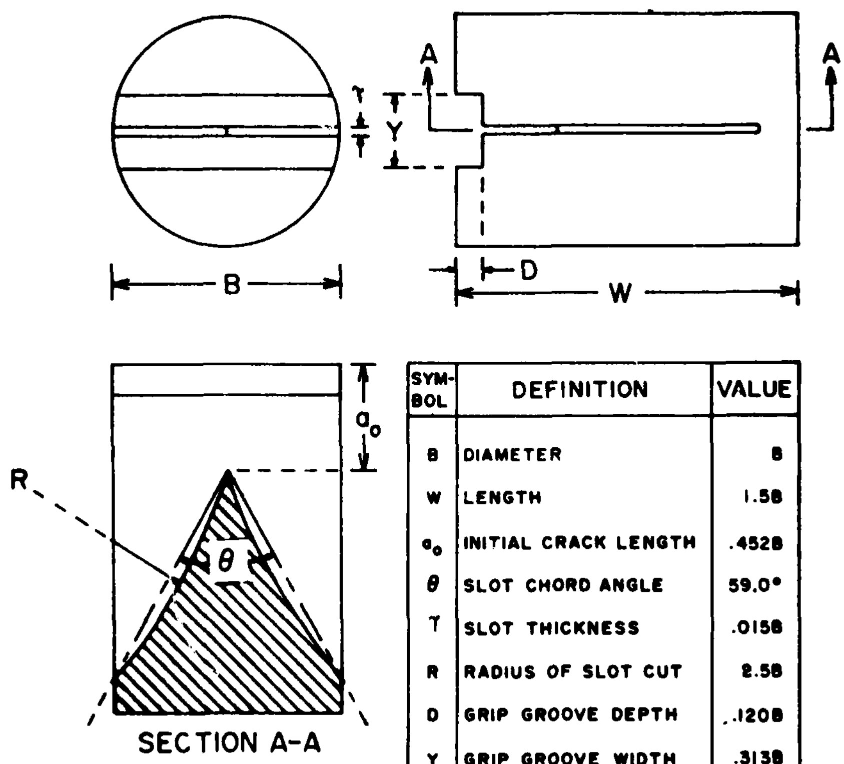
TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Although fracture mechanics can play a very important role in military hardware design and quality assurance, the difficulty of measuring the fracture toughness of materials has hindered the use of fracture mechanics considerations. The recently developed short rod method has shown the potential for alleviating many of the former difficulties of measuring fracture toughness. Therefore, the Army Materials and Mechanics Research Center has supported the further development and testing of the short rod method through a contract with Terra Tek, Inc., where the method was first conceived. Figure 1 shows the short rod specimen configuration.



SYMBOL	DEFINITION	VALUE
B	DIAMETER	B
W	LENGTH	1.5B
a_o	INITIAL CRACK LENGTH	.452B
θ	SLOT CHORD ANGLE	59.0°
τ	SLOT THICKNESS	.015B
R	RADIUS OF SLOT CUT	2.5B
D	GRIP GROOVE DEPTH	.120B
Y	GRIP GROOVE WIDTH	.313B

Figure 1. Short rod specimen configuration and dimensions.

The contract specified three main tasks, one of which involved a cooperative interlaboratory effort to experimentally test the agreement between fracture toughness measurements made by the short rod method and by the ASTM E 399 method.[1] The second task was to adapt the short rod test to use ultra-small specimens -- only 6.35 mm dia. by 9.53 mm long (.250 in dia. by .375 in long). Fracture toughness specimens of this size would allow inexpensive quality control testing to be done on actual HF1 steel shell casings. The last task involved a study of the effect of specimen size on the measured fracture toughness.

The contract has now been successfully completed, and the details of the effort which are given on the following pages constitute the final report. A paper on the study in which short rod fracture toughness measurements were compared with the ASTM method has already been written,[2] and that paper is included as an attachment to the final report.

The fracture toughness measurements of concern in this report are measurements of the material's plane-strain critical stress intensity factor. In keeping with ASTM usage, the symbol K_{Ic} in this paper will mean the plane-strain critical stress intensity factor as measured by the ASTM E 399 method. Measurements of the plane-strain critical stress intensity factor by the short rod method will be symbolized by K_{IcSR}.

SHORT ROD TEST APPARATUS

All of the 25.4 mm diameter specimens of this study were tested on the Terra Tek Fractometer II System[3] which has been specifically designed for convenience and accuracy in testing short rod specimens. The Fractometer II uses a Fracjack specimen loading mechanism* whose principle of operation is illustrated in Figure 2. As can be seen, the grips which open the specimen mouth are pivoted about a point such that the grips rotate approximately the same amount as the specimen's grip surfaces on which the grips pull. This increases the accuracy of the test by tending to keep the line of contact between the grip and the specimen's grip surface constant during the test. The Fracjack further enhances the accuracy of the test by making an automatic error compensation for any deviation in the load line which may occur either during the test or because of imperfect specimen grip groove fabrication. The mechanism by which the Fracjack accomplishes the automatic compensation for load-line deviation is discussed in Reference 3.

Since no apparatus existed for testing the ultra-small short rod specimens of this study, a special Fracjack mechanism was designed and constructed to test both the 12.7 mm and the 6.35 mm diameter specimens. A photograph of the device appears in Figure 3. The rather massive design assures a very high stiffness of the Fracjack, such that the tests can be run under controlled displacement conditions. A high stiffness of the test machine is particularly desirable when testing materials which exhibit a crack-tip instability in which the crack tends to advance in a series of rapid jumps rather than smoothly. The HF1 steel of this study is such a material. The Fracjack

* Patent applied for.

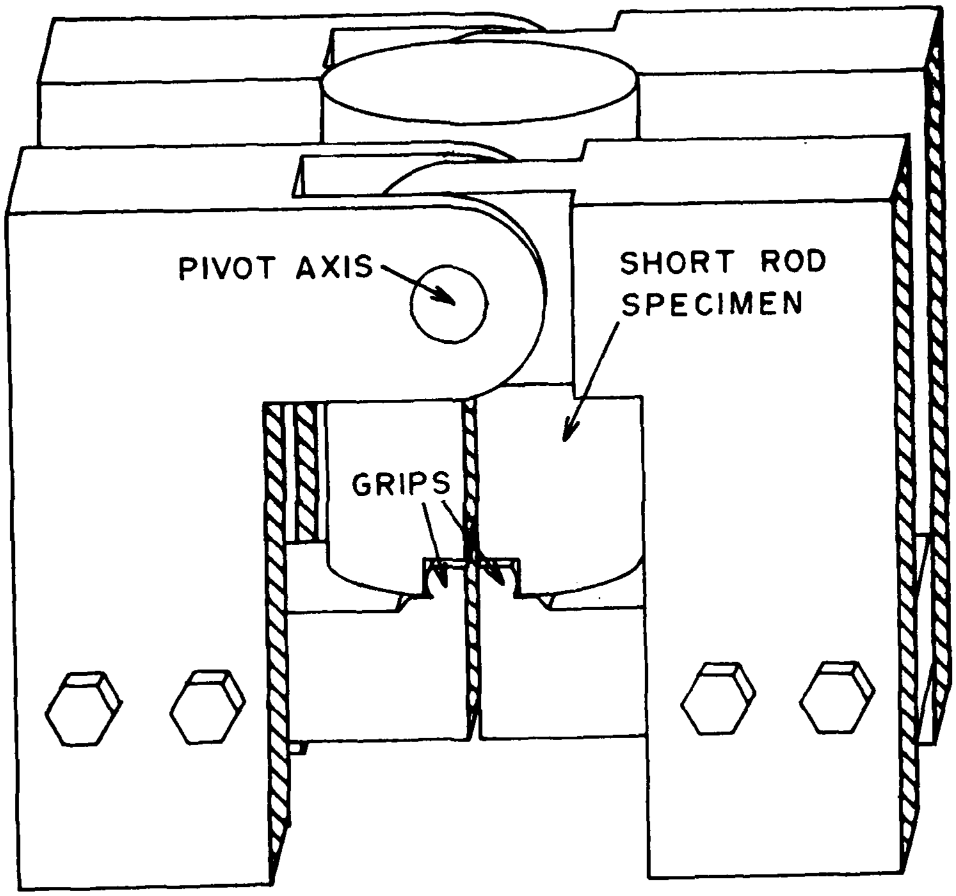


Figure 2. Schematic of the Fracjack mechanism for testing short rod specimens.

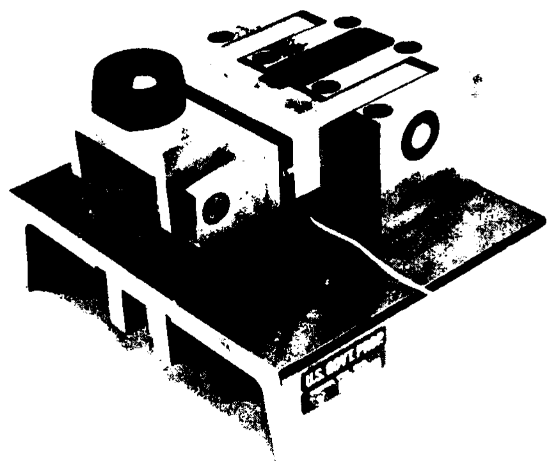


Figure 3. Fracjack designed and built to test the 12.7 mm and the 6.35 mm diameter specimens.

shown in Figure 3 has proved to be extremely stiff, and has performed extremely well in the testing of HF1 material.

The loading of the specimens is accomplished by hand-turning the knob on top of the Fracjack. A modified Fractometer I mouth opening gage is used to measure the mouth opening displacement of the 6.35 mm diameter specimens, while a standard Fractometer I gage is used when testing 12.7 mm diameter specimens.

The Fracjack of Figure 3 was designed and constructed in partial fulfillment of the contract of this report, and is therefore the property of AMMRC. As mentioned previously, the 25.4 mm diameter specimens were tested on the Terra Tek Fractometer II test machine. A prototype Fracjack for 50.8 mm diameter specimens, constructed by Terra Tek with in-house funding, was used to test the four 50.8 mm diameter specimens included in one of the size effect studies. These were the only specimens larger than 25.4 mm diameter which were tested under the present contract.

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DATA REDUCTION

The various types of load vs. mouth opening records which have been observed in short rod fracture toughness tests of many different materials are illustrated in Figure 4. The data reduction procedures for all but the crack jump specimen behavior of Figure 4c are outlined in Reference 4. Since many of the tests of this study had the crack jump behavior, and inasmuch as the data reduction procedure for this type of test differs from that for the specimens which provide a more smooth load-displacement record, the method of obtaining the K_{IcSR} values from test records showing crack jumps will be summarized here.

The equation for the plane-strain critical stress intensity factor for a short rod fracture toughness test is[4]

$$K_{IcSR} = AF/B^{3/2} \quad , \tag{1}$$

in which B is the specimen diameter, F is the load required to advance the crack, and A is a function of the scaled crack length, a/B. In specimens which produce a smooth load-displacement record, and which obey the principles of linear elastic fracture mechanics (LEFM), it can be shown[5] that for a given specimen geometry, the scaled crack length is always the same at the time of the peak load in the experiment. Therefore, for LEFM specimens of a given geometry, the dimensionless function A always has the same value at the time of the peak load. K_{IcSR} is thus directly proportional to the peak load, and there is no need to measure the crack length in the test. However, in some materials such as HF1 steel, the crack advances by large jumps instead of smoothly. The crack seldom stops at the location corresponding to that of the peak load in a smooth test record, and one must therefore evaluate A at the crack length of one or more of the crack jump positions in order to calculate K_{IcSR}.

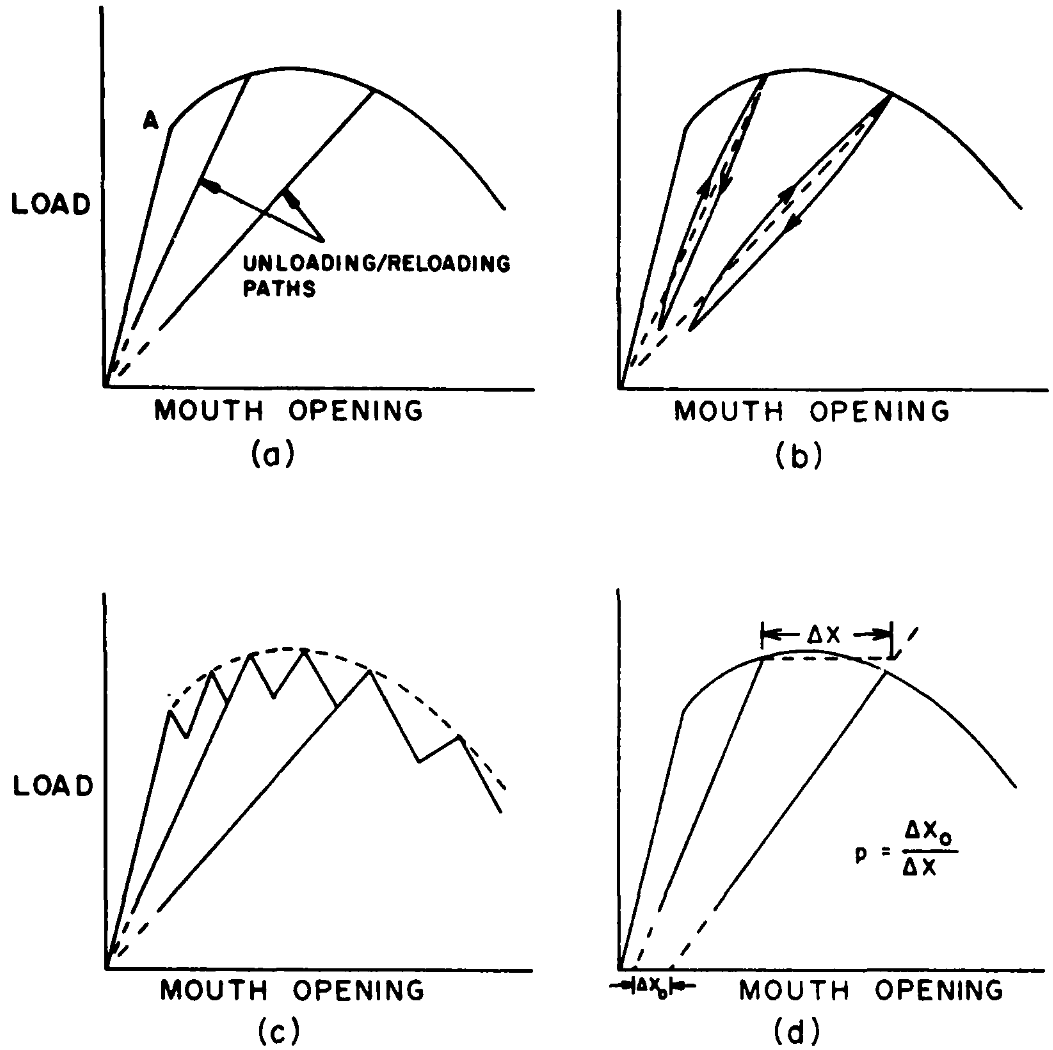

Figure 4. Types of load vs. mouth opening curves observed. (a) Ideal LEFM curve. (b) Hysteresis in unloading/reloading paths. (c) Crack jumps. (d) Elastic-plastic specimen response.

For a given scaled specimen geometry, A is a single-valued function only of the scaled crack length, a/B, independent of the specimen material. Also for a given geometrical configuration, the scaled crack length is a single-valued function of the specimen compliance ratio, c_0/c, where c_0 is the initial elastic compliance before the initiation of any crack, and c is the compliance at the crack length in question. Therefore, A can be written as a function of the compliance ratio:

$$A = A(c_0/c) \qquad (2)$$

The compliance ratio is easily obtained from the test record by dividing the relaxation slope at the crack length in question by the slope of the initial elastic loading path. The value of A as a function of c_0/c was therefore obtained experimentally (Figure 5) and was used in the evaluation of K_{IcSR}. As an example, the release slopes and the initial elastic loading slope of the record of Figure 6 were used in Figure 5 to obtain the value of A at the time of the crack jump which occurred at the second peak in the record. The load, F, at the second peak, together with A, defined the K_{IcSR} value through Equation 1. Another value of K_{IcSR} could have been obtained from the same specimen by using the crack jump which initiated at the third peak in the test record where the compliance ratio was .21. However, A is best-defined in the compliance ratio range $0.60 > c_0/c > 0.25$. Therefore, only those crack jumps which occurred within this compliance ratio range were used in the data analysis.

The analysis procedure outlined above was used in all of the tests of HF1 material, inasmuch as this material always displayed the crack jump behavior. A sample calculation of this type is given in Appendix A.

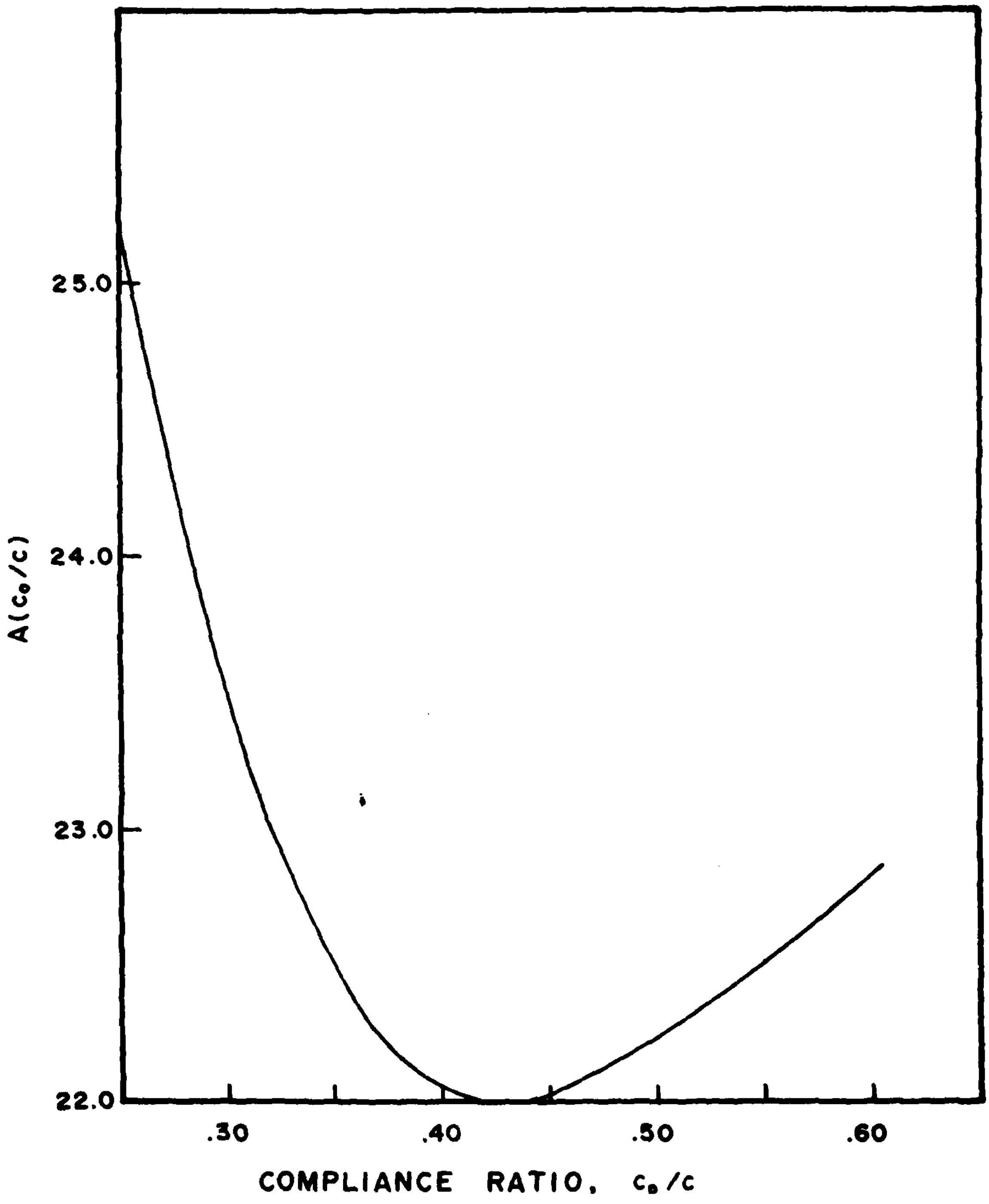

Figure 5. This curve of A vs. c_o/c is used in the data reduction of short rod specimens having the crack jump behavior.

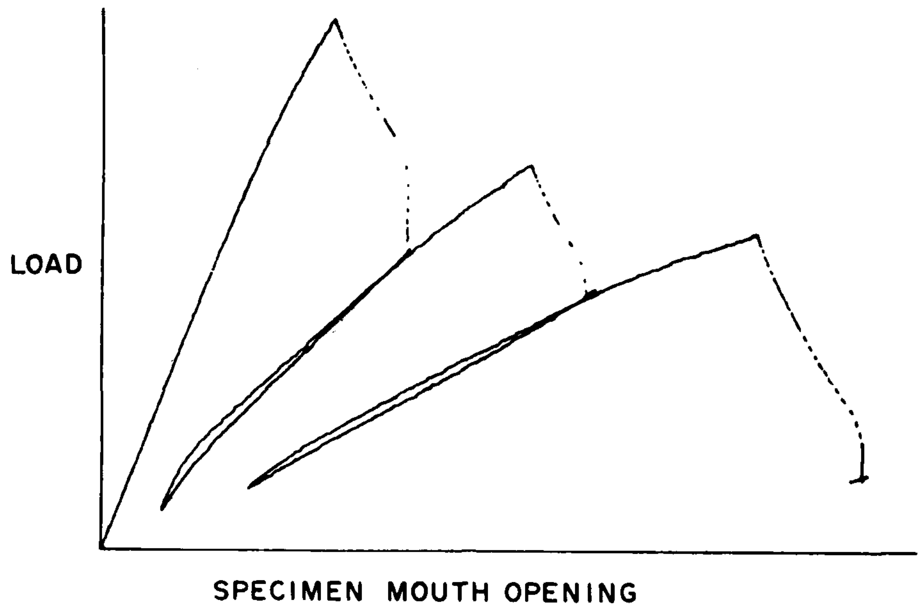

Figure 6. Load vs. mouth opening record of Specimen No. 7 of the ultra-small short rod specimen study.

The 4340 steel, on the other hand, always produced the more smooth load-displacement record. The 4340 data were therefore always analyzed according to the principles outlined in Reference 4, in which a limited amount of elastic-plastic behavior of the specimen can be accounted for such that the fracture toughness measurement remains valid.

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THE K_{Ic} COMPARISON STUDY

This study has already been reported in a paper by L.M. Barker of Terra Tek and F.I. Baratta of AMMRC.[2] The paper is included as an attachment to this report; therefore, the study is only briefly summarized here. The objective of the study was to compare short rod K_{IcSR} measurements with K_{Ic}'s measured according to ASTM E 399 to obtain an indication of the validity and accuracy of the short rod measurement technique. In order to obtain completely unbiased data, the K_{Ic} measurements were made at other laboratories, and the K_{Ic} values were not made known to the K_{IcSR} measuring laboratory (Terra Tek) until after all of the K_{Ic} and K_{IcSR} values had been reported to AMMRC. To assure as near identical material as possible the short rod specimens were machined from the tested ASTM compact specimen halves which had already been tested by the participating laboratories.

Several steels, several aluminum alloys, and a titanium alloy were included in the study. Five different laboratories furnished the K_{Ic} values and the tested specimen halves, while all of the K_{IcSR} tests were done at Terra Tek using the Fractometer II System.

The test results showed remarkably good agreement between the K_{Ic} and K_{IcSR} measurements, considering the tests were done at a number of different laboratories and used different fracture toughness measurement methods. The K_{IcSR} values averaged 6% smaller than the K_{Ic}'s. However, the K_{IcSR} values were well clustered at the 6% low point -- the average difference from the 6% low figure was ± 4%. Inasmuch as the original calibration[5] of the short rod specimen configuration was determined only to ± 7%, and considering that the specimen geometry and loading configuration has evolved somewhat since the original calibration, the 6% low average is considered an excellent agreement.

The present K_{Ic} - K_{IcSR} comparison study can be used as a re-calibration study for the short rod specimen, particularly since it constituted a much broader, more detailed study than the original calibration. In addition, a recent experimental compliance calibration study[6] has also indicated that the short rod calibration constant should be increased. Nevertheless, one should be cautious in changing the calibration of the specimen. It would seem better to remain slightly on the low side for reasons of conservatism than to overshoot to too high a calibration. For these reasons, it was decided to increase the calibration constant for the short rod specimen by 4%. The revised calibration was used for all of the K_{IcSR} measurements made for the other tasks of this report.

ULTRA-SMALL SHORT ROD SPECIMENS

The objectives of this study were to develop the techniques for preparing and testing ultra-small short rod specimens, and to test a number of the specimens to determine the agreement with pre-cracked charpy tests of HF1 fragmentation shell casing material. The specimen size selected was 6.35 mm diameter by 9.53 mm long. Such a specimen is small enough to test the fracture toughness at any crack orientation in certain HF1 steel shell casings of interest to the Army.

Basically the same specimen preparation techniques as used for larger specimens were adapted for the preparation of the ultra-small specimens. A special specimen holder was designed and made to facilitate the cutting of the slots with a diamond saw blade. A commercial diamond blade of 76 mm diameter and .15 mm thickness was found satisfactory for the slotting. It produced an approximate linear scaling of the slot thickness used in larger short rod specimens. A photograph of an ultra-small specimen and the specimen holder for sawing appears in Figure 7. Figure 8 shows an ultra-small specimen being slotted by the saw.

The short rod specimens were made from the tested halves of six pre-cracked charpy specimens furnished by AMMRC. The preparation and testing of the precracked charpy specimens, as well as the mechanical properties measurements of the HF1 material, have been described by Bruggeman and Smith.[7] Briefly, the charpy specimens were taken from the sidewalls of actual M549 projectile warheads. They were oriented longitudinally, and the precrack was always located on the outside of the projectile with the crack propagation direction inward. At least two such charpy specimens were tested from each

Figure 7. An ultra-small short rod specimen, and a second speciman installed in the special holder for the slotting operation.

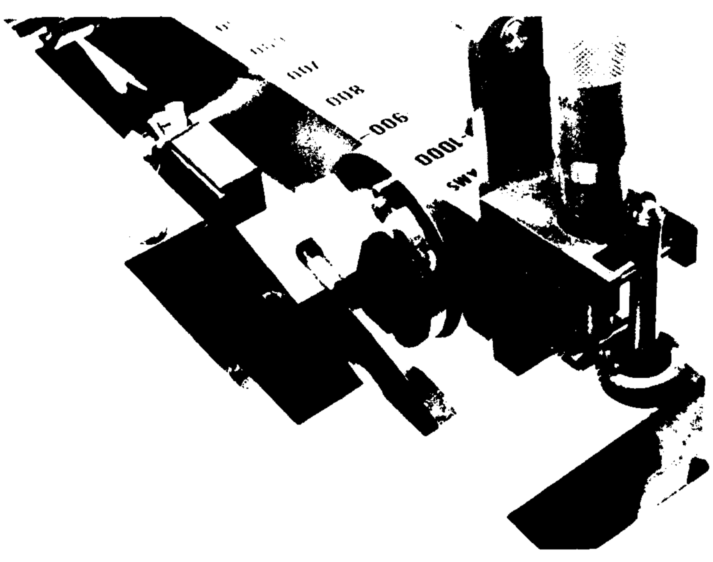

Figure 8. Slotting an ultra-small specimen.

warhead but only one of these was used to make the ultra-small short rod specimens of this study. The mechanical properties of the material of each charpy specimen, as reported in Ref. 7, are shown in Table I.

TABLE I - MECHANICAL PROPERTIES OF CHARPY SPECIMENS

AMMRC Spec. No.	Y.S. (MPa)	U.T.S. (MPa)	ELONG. (%)	R.A. (%)
3S-4	1054	1256	9.0	23.1
4S-3	983	1267	7.0	17.0
5S-3	1048	1219	8.5	22.3
7S-4	1011	1299	8.5	20.5
20S-3	1055	1265	7.7	21.6
32S-2	1113	1335	7.2	12.8

Before machining the short rod specimens, the fracture surfaces of the precracked charpy specimens were sawed off and saved for future reference. The short rod specimens were then machined from the remaining material such that the crack orientation in the short rod would be the same as that of the parent precracked charpy specimen. Two short rod specimens were prepared from the broken halves of each charpy specimen. Inasmuch as these were the first short rod specimens of such a small size ever prepared, the techniques of properly sawing the slots were not yet fully developed. Consequently, some of the specimens had poorly centered saw-cuts, etc. This often caused poor test performance, such as failure of the crack to follow the slots. The data from four of the twelve specimens had to be discarded for such reasons, and some of the data included in the study may be somewhat affected by the less-than-perfect specimen geometries. It may be significant that Specimen No. 7, which was best-prepared and had the best test performance, showed the best agreement with the precracked charpy test result.

The test record shown in Figure 6, which was obtained from Specimen No. 7, is typical of the test records of this test series. At the first and highest peak in the test, the crack initiated at the point of the chevron slot and "popped in" a considerable distance. Immediately after the crack arrested, a relaxation was performed to determine the change in compliance of the specimen since the initial elastic loading. Upon reloading, the crack remained almost stationary until it suddenly jumped forward again at the

TABLE II - TOUGHNESS MEASUREMENTS BY PRECRACKED CHARPY AND SHORT ROD METHODS

Warhead Source	AMMRC Spec. No.	K_{IcPCC} (MPa $\sqrt{m}$)	$\overline{K_{IcPCC}}$(a) (MPa $\sqrt{m}$)	K_{IcPCC} Std. Dev	Sh. Rod Spec. #	K_{IcSB} (MPa $\sqrt{m}$)	$\overline{K_{IcSR}}$(b) (MPa $\sqrt{m}$)	K_{IcSR} Std. Dev.	Std. Dev. of All K_{Ic} pts.	Sh. Rod (c) Comparison
Flinchbaugh Lot 2-8 Spec. 3	3S-4	48.4* 54.1 42.5 47.5	48.1	10.0%	1 2	59.4 59.5	59.4	0.1%	13.4%	+23.6%
Flinchbaugh Lot 2-13 Spec. 4	4S-3	50.7* 44.2	47.4	9.7%	3 4	-- 44.6	44.6	--	7.8%	- 5.9%
Flinchbaugh Lot 2-9 Spec. 5	5S-3	58.1* 50.7	54.4	9.6%	5 6	-- --	--	--	--	--
Flinchbaugh Lot 2-2 Spec. 2B	7S-4	42.7* 35.3	39.0	13.4%	7 8	39.6 --	39.6	--	9.5%	+ 1.5%
Norris Lot 1-3 Spec. 3	20S-3	58.7* 51.1	54.9	9.8%	9 10	39.7 45.2	42.5	9.2%	16.7%	-22.7%
Norris Lot 1-7 Spec. 3	32S-2	45.8* 39.6 38.1	41.2	9.9%	11 12	38.1 35.3	36.7	5.4%	9.9%	-10.9%
			Average	10.4%			Average	4.9%	11.5%	- 2.9%

* Charpy specimen from which the two short rods were fabricated

(a) Average K_{IcPCC}

(b) Average K_{IcSR}

(c) Short Rod Comparison $\equiv 100 \left(\overline{K_{IcSR}} - \overline{K_{IcPCC}}\right) / \overline{K_{IcPCC}}$

second peak of Figure 6. Another relaxation was then performed to determine the new complaince ratio, after which the specimen was reloaded to the third and final crack jump of the test record.

The precracked charpy and short rod fracture toughness measurements, K_{IcPCC} and K_{IcSR}, respectively, are compared in Table II. The charpy specimens from which the short rods were fabricated are indicated in the table. These particular charpy specimens, but not the others, were instrumented with COD gages, and the resulting load-displacement curves were used to calculate the K_{IcPCC} values. Bruggeman and Smith[7] stated that the analysis, which followed the ASTM E399 method, always resulted in the use of the peak load of the record to calculate K_{IcPCC}. Therefore, they used the peak load to calculate K_{IcPCC} for the other charpy specimens also, although no load-displacement record was made of those tests.

As mentioned previously, four of the short rod specimens (Nos. 3, 5, 6, and 8) gave invalid test results, usually for reasons related to imperfect specimen slotting. Thus, no K_{IcSR} values appear in Table II for these specimens. Only one value of K_{IcSR} was obtained from each specimen because only one crack jump occurred within the valid crack length region.

Table II also contains the averages and standard deviations of the K_{IcPCC} and K_{IcSR} data, plus a column showing the standard deviation of all the toughness measurements (both charpy and short rod) made on the sidewall material of each warhead. Finally, the percent differences of the average of the K_{IcSR} measurements from the average of the K_{IcPCC} measurements are listed for each warhead.

There are a number of very interesting observations that can be made from Table II. One is that although both short rod specimens from a given warhead were also made from the material of a given precracked charpy specimen, there is better agreement of the K_{IcSR}'s with the average K_{IcPCC} for the warhead than with the K_{IcPCC} of the particular charpy specimen from which the short rods were made. This suggests that the toughness fluctuates rapidly with position in the warhead sidewall, such that measurements taken only a few mm apart are no better related than those from more widely separated locations.

The data scatter which can be expected in the toughness data is indicated by the average standard deviation of 10.4% for the K_{IcPCC} values, as shown at the bottom of Table II. The average standard deviation of the K_{IcSR} measurements was only 4.9%, but this is likely a fortuitous result due to the small sample size. An important comparison is that of the standard deviations of the K_{IcPCC} data with the standard deviations of all the data points for each warhead (both K_{IcPCC}'s and K_{IcSR}'s). It is seen that the standard deviation of all data points is less than that of the K_{IcPCC} points for two of the warheads, greater for two others, and the same for the last. The averages of these two columns in Table II, 10.4% and 11.5%, show that the standard deviations are little affected, on the average, by grouping the data from the two types of toughness measurement. This, of course, is an indication of the essential equivalence of the two measurement techniques. It should be noted also that an independent study by Mulherin[8] has also shown a fracture toughness data scatter in HF1 warhead steel which is comparable to standard deviations of 10-12% or more.

Two further indications of the essential equivalence of the K_{IcPCC} and K_{IcSR} measurements are the nearly identical toughness ranges observed among all the warheads (35.3 to 58.7 MPa$\sqrt{m}$ for K_{IcPCC} and 35.3 to 59.5 MPa$\sqrt{m}$ for K_{IcSR}), and the fact that the short rod measurements are well centered with respect to the charpy measurements, i.e., there is no appreciable predominance of low K_{IcSR} measurements over high ones, nor vice-versa. These factors all indicate good agreement of the charpy and short rod measurements, in spite of the clouding effect of the rather large scatter in toughness values which seems to be a characteristic of the HF1 warhead material.

SPECIMEN SIZE EFFECT STUDIES

This phase of the program was designed to provide more data on the effect of the specimen size on the value measured for the fracture toughness, K_{IcSR}. Previous work has indicated little or no size effect, but these measurements were made mainly on aluminum[6,9] and rock,[10] whereas the primary interest here is in the HF1 steel. Furthermore, it is known from theoretical considerations that a minimum short rod diameter for a valid test must exist, and that the minimum diameter should be proportional to $(K_{IcSR}/\sigma_{ys})^2$, where σ_{ys} is the yield strength in tension. The data of Reference 6 indicate that the minimum diameter can be at least as small as $1.0 \times (K_{IcSR}/\sigma_{ys})^2$ for the 6061-T651 aluminum of that study.

MATERIAL DESCRIPTION

The materials used for the size effect studies of this report were three steels. One was 4340, and the other two were HF1 fragmentation steel taken from the same original billet but heat treated to two different conditions. The chemical compositions are given in Table III, while the heat treatments are shown in Table IV. Table V lists the mechanical properties.

The 4340 steel was purchased in the form of a 25.4 mm thick plate. From the plate, two strips were cut about 30 mm wide and 300 mm long, the length of the strips being in the transverse rolling direction of the original plate. The strips were then turned on a lathe into 25.4 mm diameter rods, 300 mm long. One of the rods was cut into the 25.4 mm diameter specimen blanks, each of which was 38.1 mm long. The 25.4 mm diameter specimens and the remaining 25.4 mm diameter rod were then heat treated, after which the 12.7 mm and 6.35 mm diameter specimens were machined from the second rod. All of the heat

TABLE III - CHEMICAL COMPOSITION OF SIZE EFFECT STUDY STEELS

	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	V	Al
4340	.40	.77	.010	.015	.32	.80	1.80	.23	--	--	--
HF1	1.02	1.75	.012	.009	.67	.11	.03	.03	.05	.004	.015

TABLE IV - HEAT TREATMENTS OF SIZE EFFECT STUDY STEELS

Material	Heat Treatment
4340	843°C salt, oil quench, temper 427°C, 1 + 1 hr.
HF1-1	870°C 2 hr air, 843°C 1 hr, oil q., temper 565°C, 2 hr.
HF1-2	870°C 3 hr air, 843°C 1 3/4 hr, oil q., temper 620°C, 3 hr.

TABLE V - MECHANICAL PROPERTIES OF SIZE EFFECT STUDY STEELS

Material	Yield (.2%) MPa (ksi)	Tensile MPa (Ksi)	Elong. (%)	R.A. (%)	Rc
4340	1330 (193)*	1500 (220)*	11.*	36*	45
HF1-1	790 (115)	1100 (160)	1.9	1.4	38
HF1-2	580 (84.4)	990 (144)	11.9	6.1	33.5

* Values estimated from heat treatment and hardness.

treatment was done on 25.4 mm diameter material before machining the final diameters of the smaller specimens to assure that the thermal history at the crack would be essentially the same for all the specimens. An objective of the specimen fabrication procedure was to keep track of the material orientation throughout the machining and heat treating operations so that the toughness would always be measured for the L-T crack orientation. Unfortunately, the orientation was lost on two of the 6.35 mm 4340 steel specimens, and their crack orientations were closer to S-T than to the desired L-T.

The HF1-1 and the HF1-2 materials were supplied already heat treated by AMMRC in the form of plates about 200 mm square. The plates were all sliced from a single 200 mm square bar of HF1 steel to assure uniform material properties. Three plates of HF1-1 were supplied, each 35 mm thick. The HF1-2 material consisted of three additional plates, each 60 mm thick.

In order to further assure uniformity of the short rod specimens, one of the 200 mm plate dimensions was labeled the L direction and the other the T direction. All of the L directions were the same relative to the original bar of material from which the plates were sliced. The short rods were then machined as L-T specimens (Figure 9). Furthermore, the specimens were machined such that the crack plane was never more than 30 mm from the center of the L-dimension on the plate, and such that the crack would always be approximately 50 mm from the edge of the plate in the T-direction when the K_{IcSR} measurement was made (See Figure 9).

The specimen sizes tested in each of the three size effect studies are shown in Figure 10.

DATA AND RESULTS

4340 Steel: The test results are summarized in Table VI. It had been planned to test six specimens of each size, but one of the 25.4 mm diameter

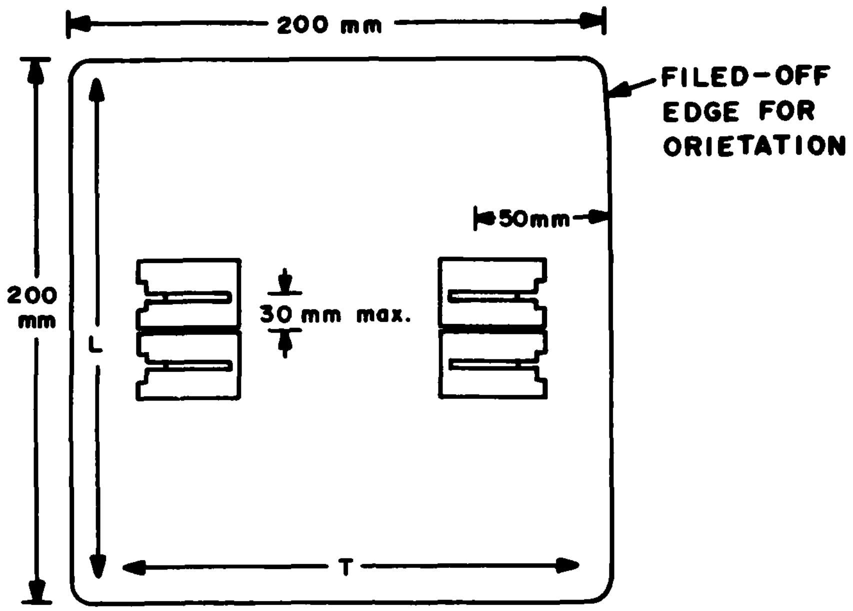

Figure 9. Showing the location and orientation of the HF1 short rod specimens relative to the supplied plates of material.

Figure 10. Specimen sizes of the three materials tested in the size effect study. The largest specimen is HF1-2 material, 50.8 mm diameter.

specimens was ruined in the preparation operations. The plasticities listed in Table VI are a measure of the degree to which the specimens deviated from the ideal LEFM behavior during the tests. By using the analytical procedures derived in Reference 4, the effects of plasticities up to a certain amount, probably 0.2 or greater, can be accounted for in the data analysis. For a given material, the plasticity should vary inversely as the specimen size. However, the 12.7 mm diameter 4340 specimens showed an appreciably smaller plasticity than the 25.4 mm specimens, which was a very surprising result. Also, the 12.7 mm diameter specimens gave K_{IcSR} values which averaged 13% lower than those of the 25.4 mm specimens. Undoubtedly, the anomalously low plasticities contributed to the lower K_{IcSR} readings of the 12.7 mm specimens. The plasticities of the L-T oriented 6.35 mm diameter specimens were much larger, as would be expected.

The orientation of two of the 6.35 mm diameter specimens relative to the original rolling direction of the plate from which they were made was unfortunately (and unknowingly) lost during fabrication. It happened that the orientation of these two specimens was much closer to S-T than to the desired L-T. It became apparent that something was wrong with one of the specimens

TABLE VI - 4340 SIZE EFFECT TEST RESULTS

No. of Specimens	Spec. Dia (mm)	Average Plasticity	Av. K_{IcSR} $MPa\sqrt{m}$	Av. K_{IcSR} $ksi\sqrt{in}$	Std. Dev.
5	25.4	.063	137.6	125.1	5.4%
6	12.7	.037	120.0	109.1	2.8%
4	6.35	.22	132.4	120.4	10.9%

when it showed a plasticty of zero and a K_{IcSR} of less than half as much as some of the other specimens. By examining the fracture surfaces, it was immediately clear that the crack orientation had been lost. Figure 11 shows a photograph of the fracture surfaces of one of the two approximately S-T specimens along side an L-T specimen. The specimen on the left, which gave the lowest K_{IcSR} value, shows clearly that the rolling direction was approximately in the plane of the crack. Thus, the orientation is approximately S-T.

In two of the four L-T 6.35 mm specimens, the crack exited to one side at approximately the critical crack length, i.e., where the K_{IcSR} measurement is taken. Thus, the data from these two may not be as significant as desired. However, the K_{IcSR} values obtained from these specimens are somewhat higher than the others, which is probably why the crack exited to one side. Thus, to omit these data could bias the average toward a lower K_{Ic} value, and thus they are retained. Note that the standard deviation of the 6.35 mm data is rather poor.

The average of the K_{IcSR} averages from the three specimen sizes is 130.0 MPA$\sqrt{m}$ (118.2 ksi$\sqrt{in}$), and the standard deviation of the averages is 7.0%. If 130.0 MPa$\sqrt{m}$ is taken as K_{IcSR}, and if the yield strength is 1330 MPa (Table V), then $(K_{IcSR}/\sigma_{ys})^2 = 9.5$5 mm, and the 6.35 mm specimens had a diameter of only $B = 0.66(K_{IcSR}/\sigma_{ys})^2$. This is significantly smaller than that which had been considered to be the specimen size limitation, namely $B \geq (K_{IcSR}/\sigma_{ys})^2$. Thus, it is gratifying that the average K_{IcSR} from the 6.35 mm diameter specimens is close to the over-all average. On the other hand, the 12.7 mm specimens had a diameter of $B = 1.33(K_{IcSR}/\sigma_{ys})^2$, and yet gave K_{IcSR} values which appear to be significantly lower than 25.4 mm results, inasmuch as the standard deviations of the two specimen sizes do not overlap. Thus, it seems unclear whether or not the present series of tests should be pronounced size-independent.

Figure 11. Magnified view of two of the 6.35 mm diameter 4340 tested specimens. The horizontal markings on the fracture surfaces of the specimen on the left show the rolling direction. The rolling direction is perpendicular to the fracture suface in the specimen on the right.

HF1-1 Steel: The fracture toughness measurement results are summarized in Table VII. Two of the four original 25.4 mm diameter specimens gave invalid data because the crack failed to follow the chevron slots sufficiently well. Also, the data from one of the 12.7 mm specimens was invalid.

As discussed in the section on data analysis, the HF1 material has the crack jump behavior during the test, and thus several values of K_{IcSR} are calculated and averaged to obtain the K_{IcSR} for each specimen. The average number of crack jumps used to calculate the K_{IcSR} for each specimen is shown in Table VII for the HF1-1 material. It can be seen that the average number of crack jumps tends to decrease as the specimen size decreases.

TABLE VII - HF1-1 SIZE EFFECT TEST RESULTS

Spec. No.	Dia. (mm)	Crack Jump K_{IcSR} Values $(MPa\sqrt{m})$	Std. Dev.	Specimen Av. K_{IcSR} $(MPa\sqrt{m})$	Av. K_{IcSR} for Spec. Size	Std. Dev.
25-1	25.4	28.1, 31.7, 30.1, 29.7, 30.6, 30.7, 30.0	3.7%	30.1	29.8	1.6%
25-2	25.4	29.8, 29.6, 28.6, 29.2, 30.4	2.2%	29.5		
13-2	12.7	30.1, 29.3, 29.8, 29.6, 29.7	1.1%	29.7	29.9	2.8%
13-3	12.7	32.2, 32.0, 32.0, 26.7	8.7%	30.8		
13-4	12.7	28.9, 30.3, 29.6, 27.8, 27.8, 30.3	3.8%	29.2		
6-1	6.35	28.5, 27.7, 29.9, 30.3, 27.6	4.3%	28.8	29.2	1.8%
6-2	6.35	29.0, 30.6	3.7%	29.8		
6-3	6.35	30.6, 29.5, 28.4, 26.5	6.0%	28.7		
6-4	6.35	29.8, 30.3, 28.7, 28.8	2.6%	29.4		

From Table V and the average K_{IcSR} of Table VII, we find that $(K_{IcSR}/\sigma_{ys})^2 = 1.4$ mm, and that even for the 6.35 mm specimens, $B = 4.5\ (K_{Ic}/\sigma_{ys})^2$. Thus, it is not surprising that we observe good specimen size independence in this material.

HF1-2 Steel: The results of fracture toughness measurements of four specimen sizes ranging from 50.8 mm to 6.35 mm are shown in Table VIII. The average number of crack jumps per specimen was much less for this heat treatment of the HF1 steel than for the HF1-1. This may partially account for the larger standard deviations within the individual specimen sizes. Nevertheless, the average K_{IcSR} values from the various specimen sizes form an extremely good grouping with a standard deviation of only 1.0%. Considering the rather large standard deviations within the 12.7 mm group and the 6.35 mm group, the 1.0% figure must be in part fortuitous. Nevertheless, it can certainly be said that these data show no specimen size effect.

For this material, $(K_{IcSR}/\sigma_{ys})^2 = 6.15$ mm, such that the 6.35 mm specimens had a diameter of $B = 0.97\ (K_{IcSR}/\sigma_{ys})^2$. Thus, the tentative criterion of $B \geqq (K_{IcSR}/\sigma_{ys})^2$ seems to have been sufficient in this case.

TABLE VIII - HFl-2 SIZE EFFECT TEST RESULTS

Spec. No.	Dia. (mm)	Crack Jump K_{IcSR} Values (MPa$\sqrt{m}$)	Std. Dev.	Specimen Av. K_{IcSR} (MPa$\sqrt{m}$)	Av. K_{IcSR} for Spec. Size	Std. Dev.
51-1	50.8	44.9, 46.2, 45.5	1.4%	45.5	45.6	2.7%
51-2	50.8	43.9	-	43.9		
51-3	50.8	47.9, 45.5	3.5%	46.8		
51-4	50.8	46.3, 46.0	0.5%	46.1		
25-1	25.4	44.0, 48.5	6.9%	46.3	45.1	3.9%
25-2	25.4	45.3, 45.8	1.2%	44.9		
25-3	25.4	47.4, 45.7	2.8%	46.5		
25-4	25.4	43.8, 41.6	3.7%	42.7		
13-1	12.7	42.2	-	42.2	45.8	12.0%
13-2	12.7	43.5, 38.8	8.1%	41.2		
13-3	12.7	53.4		53.4		
13-4	12.7	44.2, 48.3	6.3%	46.3		
6-1	6.35	49.2, 47.4, 47.9	1.9%	48.2	46.2	9.3%
6-2	6.35	49.2	-	49.2		
6-3	6.35	47.4		47.4		
6-4	6.35	39.8		39.8		

DISCUSSION

In comparing short rod data with other fracture toughness data, it should be kept in mind that the short rod makes highly localized toughness measurements. The width of the crack front is only about one-third of the specimen diameter at the time of the K_{IcSR} measurement, and therefore the toughness measurement is localized at about the central one-third the specimen diameter. Thus, for the ultra-small short rod specimens, the toughness was measured along a line in the material which was only about 2 mm long. The precracked charpy specimens of this study, on the other hand, had a crack front width of 10.0 mm. The more highly localized fracture toughness measurements of the ultra-small short rod specimens should prove an advantage in evaluating point-to-point variations in toughness. The localized measurements can be an important design consideration, because a critical flaw may occur within locally weak material, such that when it enlarges due to a local lack of toughness, it may reach the critical flaw size for the surrounding tougher material. The need for measuring the variability in toughness in HF1 steel has been stressed by Bruggeman and Smith.[7] If the local toughness varies on a scale which is smaller than the 10 mm crack front length of the charpy specimens, one might expect limited agreement between the charpy specimens and the short rod specimens made from them, as observed in the ultra-small specimen study. It would appear important, however, to establish the toughness variability using the shortest possible test crack front length. The factor of five reduction in test crack front length offered by the ultra-small short rod specimen therefore seems to be a valuable asset in evaluating the integrity of the M549 projectile warhead.

In the study of the ultra-small (6.35 mm diameter) short rod specimens of HF1 material from actual M549 warheads, there are several indications that the short rod measurements are essentially equivalent to the precracked charpy measurements, in spite of the relatively large scatter in toughness data which is a characteristic of this material.[7,8] These include the following observations:

1) The ranges of toughness values measured by the charpy and short rod methods are nearly the same.

2) The addition of the K_{IcSR} data to the K_{IcPCC} data makes little difference in the standard deviations, on the average.

3) In comparing the short rod toughness measurements of each warhead with the charpy measurements, the short rod averages are centered at only 2.9% below the charpy averages, although there is considerable scatter in the individual measurements.

4) The toughness rankings of the warheads by the charpy and short rod methods are similar. The two rankings agree to within one rank except for one warhead, where the difference is two ranks. Considering the toughness variability, the ranking agreement is probably as good as should be expected.

The short rod specimen size effect studies of HF1 material and the K_{Ic} vs K_{IcSR} comparison studies provide two additional indications that the ultra-small short rod data for warhead HF1 steel are accurate:

5) No specimen size effect was found for HF1 steels, indicating that the ultra-small specimens provide the same average toughness values as larger specimens.

6) Normal size short rod specimens of a number of materials, including HF1 steel, showed consistently good agreement with K_{Ic} measurements

made according to ASTM E 399. If normal size short rod measurements agree with E 399 results, and if ultra-small short rod measurements agree with normal size short rod measurements, then the ultra-small short rod measurements of warhead material must give an accurate prediction of what an E 399 measurement would be, if such a measurement could be made on actual warhead material.

Thus, it appears clear that the short rod method is suitable for the measurement of fracture toughness in actual HF1 warhead casing material.

In the specimen size effect study, it may be instructive to plot the standard deviations found for each size group vs. the specimen diameter scaled by dividing by $(K_{IcSR}/\sigma_{ys})^2$. In so doing, for example, the 6.35 mm specimens of 4340 steel have a scaled diameter of 0.66, and should be plotted at (0.66, 10.9), inasmuch as the standard deviation of the K_{IcSR}'s of that specimen group was 10.9%. Figure 12 shows such a plot of all of the size effect data. As can be seen, there appears to be a rough relationship between the standard deviation and the scaled specimen diameter (dashed line). This may help to explain the discrepancy between the K_{IcSR}'s of the 25.4 mm and the 12.7 mm diameter 4340 steel specimens. As mentioned previously, the standard deviations of those two data sets do not overlap,and thus seem to indicate a size dependence of the K_{IcSR} value between the 25.4 mm and the 12.7 mm specimens. However, as can be seen from Figure 12, the standard deviation of the 12.7 mm diameter specimens appears to be abnormally small, perhaps by chance. If the standard deviation were 8% instead of 2.8%, as the data of Figure 12 seem to indicate it should be, then the error flags on the 25.4 mm and the 12.7 mm data would just overlap, and the indication of a size effect would be much less pronounced, even if the average K_{IcSR}'s remained the same.

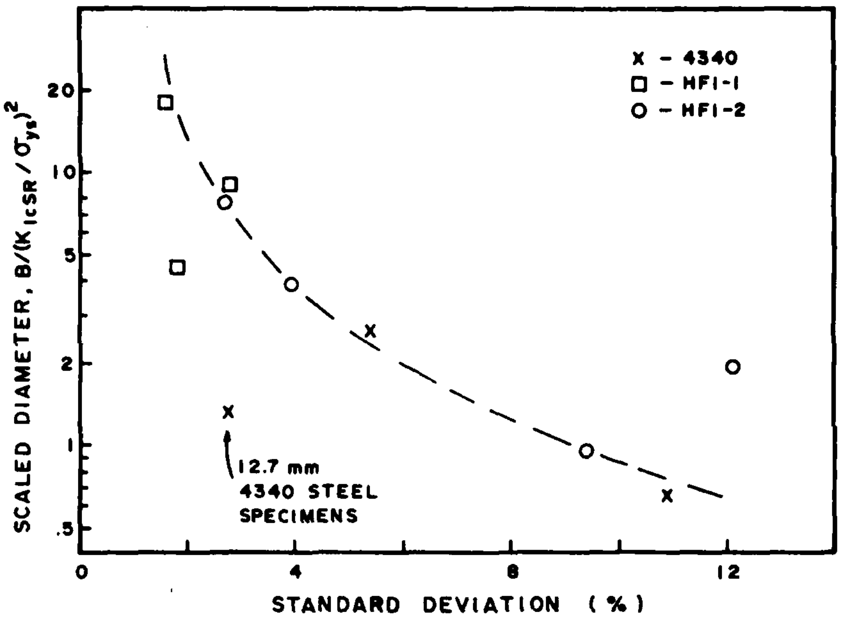

Figure 12. Relation found between the scaled specimen diameters and the standard deviation of the K_{IcSR} values.

SUMMARY AND RECOMMENDATIONS

The comparison study of the ASTM E 399 method and the short rod method of measuring fracture toughness showed a close correlation between the two techniques. The study also served as a much better comparison calibration of the short rod method than had been done before, and resulted in a calibration shift in the same direction as was indicated by an experimental compliance calibration[6] of the short rod specimen.

The techniques for fabricating and testing ultra-small (6.35 mm diameter) short rod specimens were developed. However, the art of making the specimens was initially much less than perfect, such that some of the 6.35 mm specimens of the HF1 precracked charpy comparison study were poorly prepared. This resulted in the loss of some data, and may have affected the reported data somewhat. It seems to be a characteristic of the HF1 warhead material that the toughness can vary appreciably over distances as small as a few mm. Thus, fracture toughness measurements of a given warhead by either the precracked charpy or the short rod method generally show an appreciable scatter, with standard deviations averaging up to 12%. This clouds any comparison of the two techniques based on only a few measurements. Nevertheless, several different aspects of the data of this study, when taken together, indicate conclusively that the ultra-small short rod fracture toughness measurements are in good agreement with the precracked charpy measurements. Therefore, it is recommended that the appropriate steps should be taken to adopt the simpler, less expensive short rod method as the quality control standard for the Army's fracture toughness testing of HF1 warhead material.

Specimen size effect studies were performed on 4340 steel and on two different heat treatments of HF1 fragmentation steel to determine whether ultra-small specimens can be expected to produce essentially the same toughness values as larger specimens. No specimen size effect was noted in either of the HF1 materials, which are of primary interest to AMMRC. The data on the 4340 steel seem to be inconclusive. Considering the data from all three size effect materials, a general trend toward a larger scatter in the K_{IcSR} values was apparent as the specimen size was decreased.

Finally, the testing procedure and the data analysis in testing the ultra-small HF1 specimens could be automated with the aid of a microprocessor and the appropriate auxiliary equipment. This would allow routine quality control measurements of K_{IcSR} to be made entirely by technician personnel. Inasmuch as the Army has a need for such a quality control program, it is recommended that the necessary equipment and software be developed and tested on ultra-small HF1 specimens.

APPENDIX A

Sample K_{IcSR} Calculations

The procedures used to calculate the values of K_{IcSR} for the specimens showing the crack jump behavior are outlined below, and a sample calculation is given for HF1-2 Specimen No. 25-2.

The load-displacement plot for the specimen is shown in Figure A-1, and the data analysis sheet appears in Figure A-2. A value for K_{IcSR} is calculated for each substantial crack jump which starts within the compliance ratio range of $0.25 < c_0/c < 0.60$. A "substantial" crack jump is defined as one in which the accompanying load drop is at least 2%. The average value of K_{IcSR} calculated from a given test is used as the K_{IcSR} of the specimen. The K_{IcSR} values should be calculated as follows.

1. Draw the straight-line relaxation slope lines: The slope of each straight-line drawn relaxation should be the same as the minimum

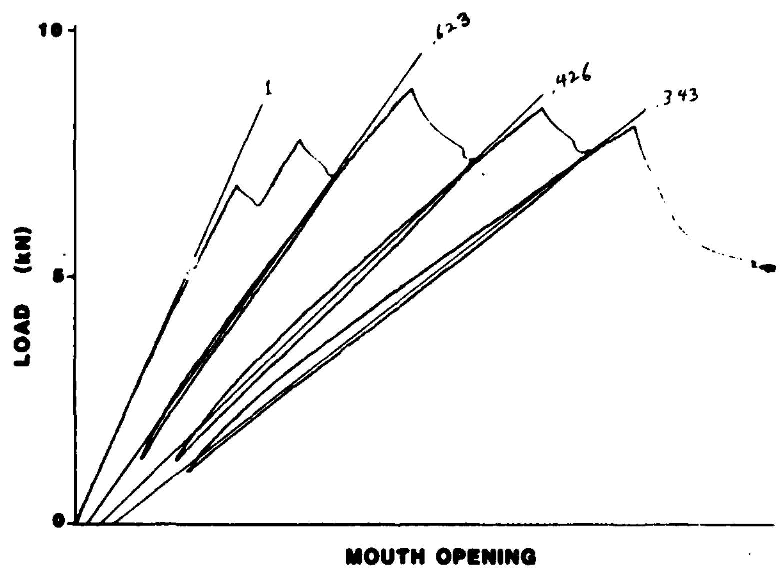

Figure A-1 Test record with data analysis constructions for HF1-2 Specimen No. 25-2 slope on the actual relaxation load-displacement path. The straight-line relaxations should be drawn through the point from which the actual relaxation was started (see Figure A-1).

2. Calculate the slope ratios: Measure the angles, ϕ_1, ϕ_2 ..., made by the drawn straight-line relaxations and the displacement axis. Also, measure the angle ϕ_o between the initial elastic loading slope and the displacement axis. Find the tangents of each of these angles. Find the desired slope ratios of the drawn straight-line relaxations by dividing the tangent of each angle, ϕ_i, by the tangent of the initial elastic loading angle, ϕ_o. The slope ratios, r_i, so calculated are the compliance ratio's, c_o/c_i, since the compliance is proportional to the inverse of the elastic slope:

$$\tan \phi/\tan \phi_o = r = c_o/c.$$

The slope ratios are written at the tops of the drawn straight-line slopes in Figure A-1.

3. Interpolate or extrapolate to estimate the unloading slope ratio r, at the initiation of each substantial crack jump. Record the estimated slope ratios that fall within the range $0.25 < r < 0.60$ on the data analysis sheet (Figure A-2).

4. For each recorded slope ratio, find the value of A_r from the graph of Figure 5. Record the A_r's next to the corresponding slope ratios on the data analysis form (Figure A-2).

5. Find the load F, at the initiation of each crack jump. Record the loads next to the corresponding r and A_r values.

6. Note the hysteresis in load, ΔF_H, at the mid-point of the actual unloading-reloading cycle closest to each crack jump. Enter the ΔF_H values next to the corresponding r, A_r, and F values.

FRACTOMETER II DATA ANALYSIS

CRACK JUMP CASE

SPECIMEN NO.	SLOPE RATIO, r	A_r	F (kN)	ΔF_H (kN)	C_c	K_{IcSR} ($MPa\sqrt{m}$)	AV. K_{IcSR}	COMMENTS
25-2	.42 .34	22.00 22.64	8.64 8.10	.40 .40	1.009	45.3 44.6	44.9	

ΔF_H = HYSTERESIS OPENING

C_c - SPECIMEN CONFIGURATION CORRECTION FACTOR

$K_{IcSR} = A_r C_c(F - \frac{1}{2}\Delta F_H)/B^{3/2}$

Figure A-2. Data Analysis Form

7. Enter the value of C_c on the data analysis form. C_c is a factor close to unity which corrects for any slightly non-standard geometry of the specimen in question. In the case of the specimen of this illustration, the angle of the chevron V slot was 0.9° too small, which required a C_c factor of 1.009. If all of the dimensions of the specimen are within tolerance, C_c = 1.000.
8. Calculate $K_{IcSR} = A_r C_c(F-\frac{1}{2}\Delta F_H)/B^{3/2}$ for each crack jump, and enter on the data analysis form. B is the specimen diameter, and is equal to 0.0254 m for the specimen of this illustration.

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Test Methods

Three separate investigations were undertaken to determine the application of the short rod fracture toughness measurement method to materials such as HF1 fragmentation steel, which is of particular interest to the Army. In the first study, short rod fracture toughness (K_{IcSR}) measurements were compared with ASTM E 399 measurements of toughness (K_{Ic}) in a number of metallic materials. Very good agreement was found. In the second study, the methods of fabricating and testing ultra-small short rod specimens (6.35 mm diameter) were developed and used in measurements of HF1 material taken from actual shell castings. The agreement of the ultra-small short rod measurements with the toughness as measured by precracked charpy specimens of the same material was rather poor. The third study was made to determine the sensitivity of the short rod toughness measurement to the size of the specimen used in the test. Short rods of various sizes of 4340 steel and two heat treatments of HF1 steel were tested. The specimen size independence of the 4340 steel was marginal, but it was excellent for the HF1 steel. A trend toward an increasing scatter in K_{IcSR} data with decreasing specimen size was noted. Recommendations for decreasing the data scatter and automating the test are made.

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EVALUATION OF A NEW FRACTURE TOUGHNESS MEASURING TECHNIQUE, AND ADAPTATION OF THE TECHNIQUE TO USE ULTRA-SMALL SPECIMENS
Lynn M. Barker - Terra Tek, Inc.
Francis I. Baratta - AMMRC

Technical Report Report AMMRC TR 79-53, Sept.1980,
41 pp. illus-tables, Contract DAAG46-78-C-0040
Final Report

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